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'Adaptive cycles' and climate fluctuations: a case study from Linear Pottery Culture in western Central Europe

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ABSTRACT

By applying cycle-based resilience theory the dynamics of the Early Neolithic west-central European Linear Pottery Culture (LBK) are investigated. These are interpreted as resulting from a combination of internal socio-economic processes as well as external environmental parameters. Resilience theory is helpful in understanding periods of increased vulnerability and inherent trends to social complexity. Cycles and threshold levels also help to understand why societies experience periods of increasing fragility and subsequent decline.

Results are based on the correlation of a typology and dendrochronology-based archaeological chronology for western LBK and various palaeoclimatic proxy-data. The ^{14}C-production curve is taken as an indicator for solar activity fluctuations, and an age model for laminated sediments as an indicator for rainfall fluctuations. We currently consider this correlation as agreeably robust; however future fine-dating may result in slight shifts within the archaeological chronology.

According to the applied age model, the simple farming societies of the LBK (5600–4900 cal BC) in west-central Europe were not immediately and devastatingly affected by most climate fluctuations. Yet, they might have been one destabilising component within broader processes. However, periods of decreased or irregularly spaced rainfall are contemporaneous to periods of population decline, while periods of increased rainfall may have favoured population growth. Towards the end of the 6th millennium cal BC, the final years of LBK in western Central Europe are contemporaneous to a general trend to less rainfall punctuated by short-term increases in precipitation. During this climatically highly volatile period LBK reaches its highest population rates and at the same time experiences a period of warfare. Thereafter population rates decline and LBK gradually vanishes from the archaeological record, being replaced by Middle Neolithic societies.

1. Introduction

Holocene climate fluctuations and their effects on past and present human societies have become one of the major research topics in archaeology and related fields. In the past two decades a great number of historic events – notably crises or collapses – have been attributed to climate triggering (e.g. Weiss and Bradley, 2001; Medina-Elizade and Rohling, 2012; Anderson et al., 2007; Migowski et al., 2006; Weninger et al., 2009; Smith, 2007). However, many scholars within the humanities – among them archaeologists – have remained sceptical when it comes to all too deterministic conclusions about how societies were, are and will be affected by climate. While some scholars outrightly neglect any major influence of climate fluctuations on history, others call for a careful examination of the complicated networks of interrelations (e.g. Dearing, 2006; Casaldine and Turney, 2010; Coombes and Barber, 2005).

Here we present hypotheses on possible effects of mid-Holocene climate fluctuations on early farming societies in temperate woodland environments, namely the Linear Pottery Culture (*LBK* – after German *Linienbandkeramische Kultur*). LBK emerged in the western Carpathian Basin as a result of contacts between farmers of the Starčevo–Körös–Criş Complex and surrounding hunter–gatherer populations (Pavúk, 2004; Bánffy and Oross, 2010; Eichmann et al., 2010). Genetically (mtDNA) LBK

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societies appear to be ultimately and to a large extend of non-European and quite possibly Near Eastern origin, with only minimal genetic influx from the Eurasian Late Pleistocene/Early Holocene hunter–gatherer societies (Bramanti et al., 2009; Haak et al., 2010; Pinhasi et al., 2012).

From its core-zone in the western Carpathian Basin LBK spread west-ward, north-ward and northeast-ward (Schier, 2009; Kreuz, 2010) (Fig. 1). Expansion occurred in shifts: wide areas were settled by small pioneer hamlets or villages which became the centres for regional and local internal colonization. This process had initially been studied in the Rhineland (Stehli, 1989) but is repeated in many other, less well researched regions. The Rhineland case had made its way into the textbooks (Renfrew and Bahn, 2005, 52–53).

While detailed anthropological and archaeogenetic work on the LBK expansion is still wanting, the archaeological evidence is interpreted as reflecting an expansion maintained by and organized through social segments sometimes termed “lineages” (Frirdich, 2005; Petrasch, 2012) or “clans” (Bogaard et al., 2011). Expanding segmentary societies, observed by African ethnography, have served as social model approximations (Gronenborn, 2003). Such social segments may be visible in the archaeological record through certain pottery motifs or figurine types which are distributed over vast areas (Frirdich, 2005, 103–104; Strien, 2005, 2010b). In the process of expansion, LBK communities increasingly interacted with regional hunter–gatherer or hunter–gatherer–pastoralists; this is agreeably well researched for the west (Allard, 2005; Jeunesse, 2001; Jeunesse and van Willigen, 2010). Out of this interaction resulted multi-traditional communities composed out of LBK segments and hunter–gatherer groups (Strien, 2005; Gronenborn, 2007a).

With the decline around and after 5000 cal BC, post-LBK Stroke-Ornamented Pottery (STK – German *Stichbandkeramik*) continued to exist in eastern Central and Eastern Europe. In the west societies came under influence of the Mediterranean Neolithic and merged into the Cerny Culture, Hinkelstein (HST) and Großgartach (GGT), finally Rössen.

2. Theory

Palaeoclimatology-informed archaeology will have to be guided by a robust theoretical tool-box. Otherwise approaches may be all too deterministic and may not go much beyond simplistic chronological correlation (Coombes and Barber, 2005). In the past numerous schemes of the possible effects of climate fluctuations on societies have been published (e.g. Pfister and Brázdil, 2006). Basically all follow the same line of argument with societies being driven into crises situations through outside forcing, reacting to these threats by social, political and economic reorganisation. Following this basic approach the archaeological chronologies were brought in as close a relation as possible with more or less suitable palaeoclimatc age models. If, within the limits of dating uncertainties, a correlation was to be postulated conclusions were drawn.

Central to such an approach are first and foremost the problems around dating precision and age model correlation. Only with reliable archaeological chronologies and fine-graded palaeoclimatical age models may robust cause-and-effect hypothesis be formulated.

Beyond chronological problems, such event-orientated approaches also quite often failed in explaining exactly how climate fluctuations affected people on the ground. They mostly focused on periods of allegedly unfavourable climate, leaving out periods during which societies would flourish (Casaldine and Turney, 2010). Moreover, if text sources could be added to the analyses, causalities were even more difficult to determine.

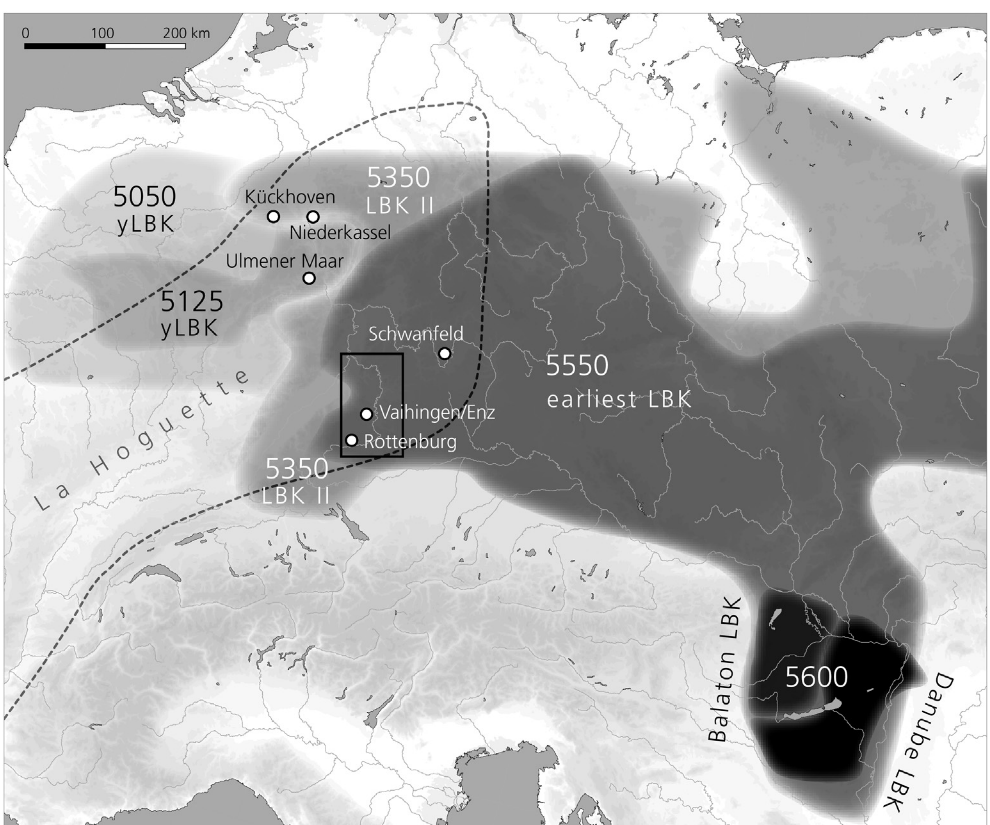

Fig. 1. Expansion of Linear Pottery Culture to the west with sites mentioned in the text. Dates are denBC (see text). Württemberg study area is boxed.

In order to step beyond these endeavours solely relying on data-correlation and fluctuation intensity palaeoclimatology-informed archaeology would need to go into a third dimension and consider the socio-economic sphere. This has been suggested by Coombes and Barber (2005) who, following Brunk (2002) from the academic field of theoretical politics, had introduced nonlinear dynamics and chaos theory into climate-related archaeology. Based on the observation that within the nonlinear dynamics paradigm systems will reach stages of instability and collapse rather unpredictably without any apparent outside influence ("complexity cascades"), they questioned climate-determinism in general. In order to single out cases where climate may have operated as a parameter for socio-economic change or even collapse Coombes and Barber (2005, 308) suggest a number of indicators, namely the abandonment of marginal zones, changes in modes of agricultural production, and the collapse of social organisation in core and periphery regions.

Apart from nonlinear dynamics another body of theory might be helpful in understanding the possible role of climate fluctuations on the dynamics of societies, namely cycle-based theories. Cycle-based theories have a great antiquity, going back to ancient Greek historiography (Ryffel, 1949). Recently culture-historical narratives have been examined by applying mathematical modelling searching for regularities and determining social, economic or ecological parameters for the rise and decline of societies (Turchin, 2003, 2006; Turchin and Nefedov, 2009). Cycle-based theories are also applied in archaeological methodology and theory: For instance are common typochronological tools like seriation and correspondence analysis (Greenacre, 2007) based on cycles of appearance, flourishing and disappearance of artefacts. On the theoretical side, cycle-based thinking is emphasised in resilience theory (e.g. Redman, 2005; Dearing, 2008; McAnany and Yoffee, 2010).

The concept of resilience originally emerged within psychology and sociology where it described how individuals or groups coped with external stress. Later resilience theory was introduced to the ecological sciences and was further developed and adapted to the analysis of ecosystems and the interaction of humans within and with ecosystems (Holling, 1973). In this course Holling and Gunderson (2002) developed a theoretical model according to which any system will undergo series of changes along a loop spanning between the parameters resilience, vulnerability, potential and connectivity. This loop was termed "adaptive cycle" thereby signalling that systems attempt to stay in a given stage as long as they are able to maintain this stage. If internal or external impulses make it necessary the system would move to the next stage. These stages were given symbols by Holling and Gunderson (2002), indicating their characteristics: the loop sets out with the α-stage and terminates with the Ω-stage. Both terms were obviously adapted from Christian-occidental symbolism. The space between the beginning and end of each loop is filled by the r- and the K-stage, termed after the r- and K-strategies of biogeography. The r-stage is characterised by an extensive expansion, the K-stage by the conservation and intensification of the previously achieved.

Holling and Gunderson (2002) depicted these cycles in the form of a "∞" thereby symbolising the eternal nature of the process. However a mathematical model developed by Bub (2011) has produced a visualisation in the form of a triangle (Fig. 2a). Cycles are nested, with long-term sequences being composed of many short-term ones (Fig. 2b). These differently spaced cycles operate at different speeds and levels; information is transferred between these levels but also between earlier and subsequent cycles (Dearing, 2008, 118). Apart from a visualisation in the form of a triangle we have also changed the parameter "connectivity" into "complexity" thereby using a term to which archaeology is more acquainted with.

Resilience theory with adaptive cycles as its conceptual backbone has the advantage, that systems – in this case human societies – are understood as holistic phenomena, being embedded in their environment. As in many other cycle-based theories crises and collapse are not singled out but are seen as stages in broader processes which follow from and again lead to phases of stability and growth. In this, adaptive cycles are inherently dynamic with continuous change being a central part of the theory. It is particularly the dynamic nature of the adaptive cycle which is useful for archaeology as it alters the common perception of history as a succession of steady states to processes in continuous change. Furthermore, the concept of resilience is very useful in palaeoclimatology-informed archaeology as it describes a system's capacity "to tolerate disturbance without collapsing into a qualitatively different state controlled by a different set of processes" (Resilience Alliance, 2012). This definition may be applied to ecosystems as well as to human societies. Climate fluctuations – as external disturbances – are thus unable to affect a society's capacity to flourish until resilience decreases and societies are no longer able to withstand (Fig. 2c). Then entities collapse and/or transform into new cycles.

Despite its proximity to processual thinking, cycle-based theories may actually help to bridge the gap between humanities and science. Humanities currently emphasise agency and historical particularity while the natural sciences emphasise system processes. Cycles in Resilience Theory may therefore be conceived as processes whose form and direction is determined by economical and ecological limiting values within which agency, socio-political structure, and ultimately human individuality may unfold. Cycles should be understood as approximations indicating tendencies and stages with fluid transitions from one stage to the other and from one cycle to the other.

3. Palaeoclimatological proxies

LBK emerges and thrives during a climatically volatile period of the earlier Atlantic (Gronenborn, 2007a,b; Dubouloz, 2008). Following Bond et al. (2001) this may be termed Ice Rafting Detritus-phase 5b. Ice Rafting Detritus-phases (IRD-phases) are defined by accumulation layers of lithic debris in North Atlantic deep core drillings resulting from ice-berg discharges from the northern ice-shield. This fresh-water influx may have had effects on the North Atlantic thermohaline circulation. At least some of these IRD-phases may be paralleled with periods of a less active sun (Bond et al., 2001; Barber et al., 2004), however possible mechanisms are debated (Wanner et al., 2008; Wirtz et al., 2010) and already Debret et al. (2007) questioned the hypothesis of Bond et al. (2001) that the 1500 years cycles are controlled by variations in solar activity.

Nevertheless may a decrease in solar activity – indicated by an increase in ^{14}C-production (Solanki et al., 2004) – translate to periods of colder winters in Eurasia as recently shown by Woollings et al. (2010), Lockwood et al. (2010) or Sirocko et al. (2012). Links between solar activity and fluctuations in several terrestrial western Central European proxy-data had been proposed previously, such as lake level increases (Magny, 2004), wet-shifts in bogs (Blaauw et al., 2004) or fluctuations in the River Main oak curve (Spurk et al., 2002). Also, cold events in the central Alps (Haas et al., 1998) and glacial advances in the western Alps (Burga and Perret, 1998) may be paralleled with phases of decreased solar activity. A similar connection has recently been proposed for northeastern North-America (Nichols and Huang, 2012).

Based on these observations Central and western European palaeoclimatology-informed Neolithic archaeology has interpreted the residual ^{14}C-curve or the ^{14}C-production curve as a climate

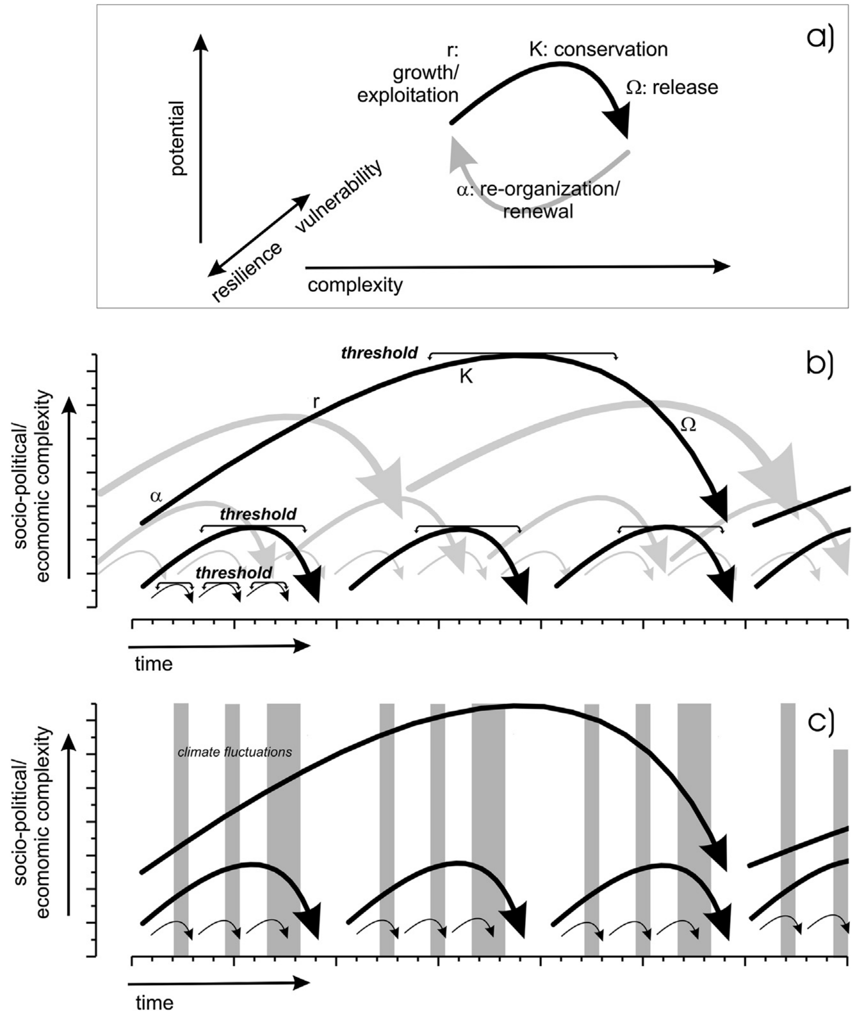

Fig. 2. Adaptive cycles from Resilience Theory (modified after Holling and Gunderson [2002] and Bub [2011]). (a) Basic build-up of adaptive cycles, (b) nested cycles in time with threshold values, (c) cycles and climate fluctuations.

proxy in itself, mainly for rainfall, less so for temperature (e.g. Maise, 2005; Arbogast et al., 2006; Dubouloz, 2008; Schibler and Jacomet, 2010; Schlichtherle, 2011). If – despite the ongoing debates about "solar forcing"-hypotheses (e.g. Rind, 2002; Bard and Frank, 2006; Lockwood, 2012) – this general association is accepted one gains the advantage that the residual ^{14}C-curve or the ^{14}C-production curve constitutes one of the best-dated general climate proxies currently available. Thus we use the ^{14}C-production curve as a proxy for precipitation and consult further local or regional proxies where available. This multi-proxy approach is demonstrated in detail in Fig. 6 where the ^{14}C-production curve and dendrochronological data from the Kückhoven well (Hinzen and Weiner, 2009) is plotted against yet unpublished laminated silt-fraction data from the Ulmener Maar in the Eifel (Sirocko et al., 2013) (Supplemental online material).

4. Linear Pottery Culture chronology in west-central Europe

As any palaeoclimatology-informed approach also the one presented here must rely on a robust archaeological chronology. The chronology of the LBK we apply is based on the "compound"-model (Germ. *Hofplatzmodell*) developed by Boelicke et al. (1988), the long-house with its surrounding pits constituting the basic chronological unit: Through correspondence analysis the ceramic assemblages from pits of an entire settlement are brought into a chronologically determined order (Strien, 2000; Kerig, 2005). Each compound or long-house is chronologically fixed by the ceramic assemblage from the surrounding pits; correspondence analysis then allows establishing a succession of houses, so-called house-generations (HG) which form a regional chronology. These regional chronologies are interconnected through combined seriation (Stehli, 1994, 132–135) but also by long-distance imports (Strien, 2009, 2010a, 503, b). Neighbouring regions tied together by imports and long-distance connections with their underlying networks suggest that they follow the same chronological scheme. For instance may the long-distance imports within the assemblage from Bochum-Hiltrop pit 25 (Strien, 2010a, 503) serve as a chronological anchor-point both for the Rhenish and the Württemberg chronologies (Fig. 3). Thus we consider the exact synchronisation between the two most elaborate regional chronologies – from the Rhineland and the Neckar Valley – as robust and also their connection to the Alsace chronology is generally accepted (Stehli, 1994, fig. 36; Strien, 2000, tab. 2.3; Lefranc, 2007, fig. 80). Admittedly, slight disagreements to other regional chronologies exist (e.g. Kneipp, 1997, Fig. 62; Hoppe, 2012) but only within a time-range of not more than half a century. These disagreements do not result from differing typo-chronologies but from different interpretations of the links between chronologies.

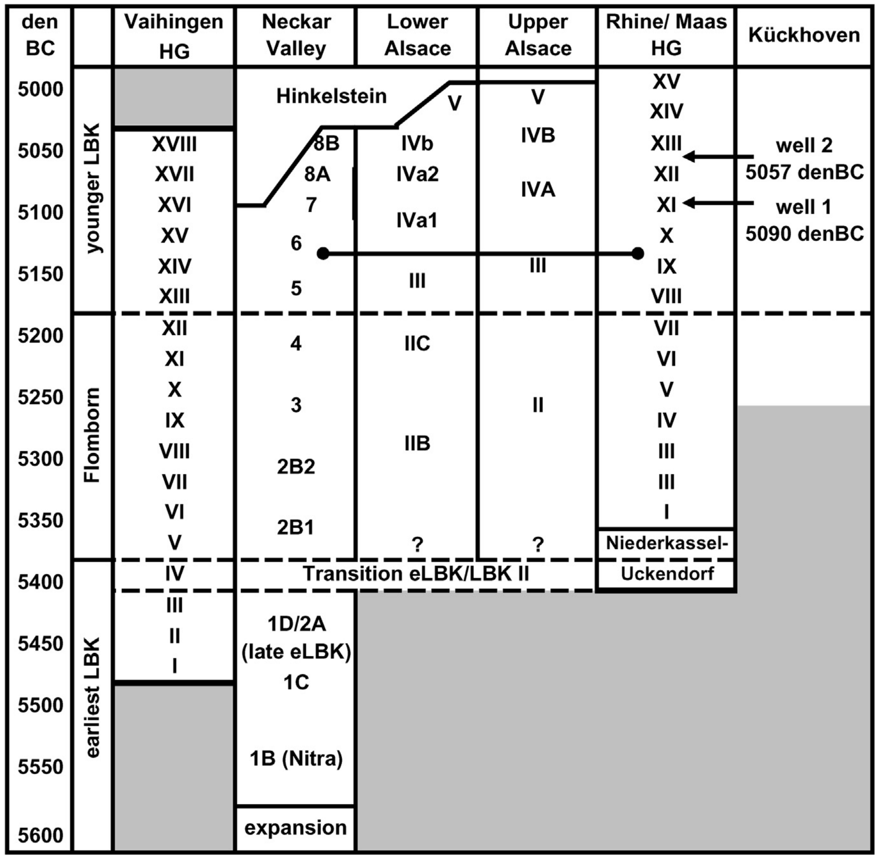

Fig. 3. Typochronological model for Linear Pottery Culture in western Central Europe (connecting line between Neckar Valley/Lower Alsace and Rhine/Maas indicates the position of the assemblage from Bochum-Hiltrop feature 25 [Strien, 2010a, 503]).

Through dendrochronological fixed-points such as the Kückhoven wooden well and the succession line of up to 14 consecutive houses in some settlements, a use-life of 23–25 years for one HG is calculated (Fig. 3). Other suggestions for use-life durations of up to 100 years (Rück, 2007) have to be dismissed as these would result in enormous population densities. Moreover, overlapping house floors in densely settled sites such as Bylany or Vaihingen make a contemporaneity of neighbouring houses impossible (Petrasch, 2012). The Kückhoven well is the only well where the initial construction phase and a later repair phase as well as the final use are fixed dendrochronologically and typologically through ceramic fragments from the filling. Thus we apply the term 'denBC' as the

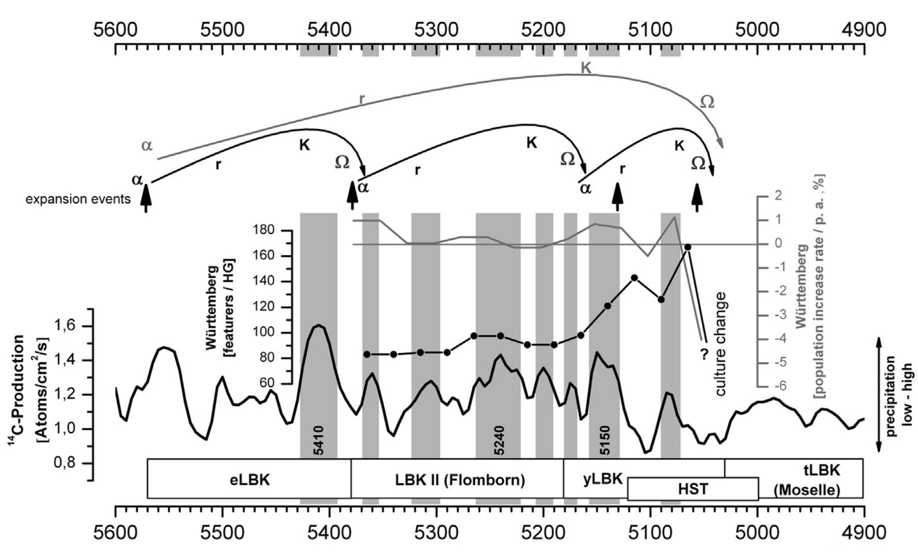

Fig. 4. Adaptive cycles and Württemberg LBK. Phases of increased rainfall are shaded (^{14}C-production rate: Kromer and Friedrich 2007).

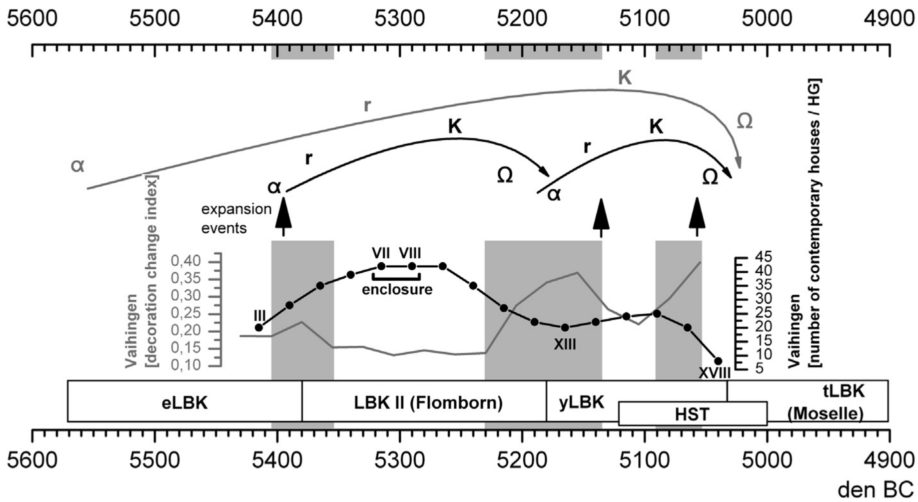

Fig. 5. Vaihingen an der Enz. Adaptive cycles, index of ceramic decoration change and number of contemporary houses (background data in Supplementary online material). Phases of social reorganisation are shaded in light grey.

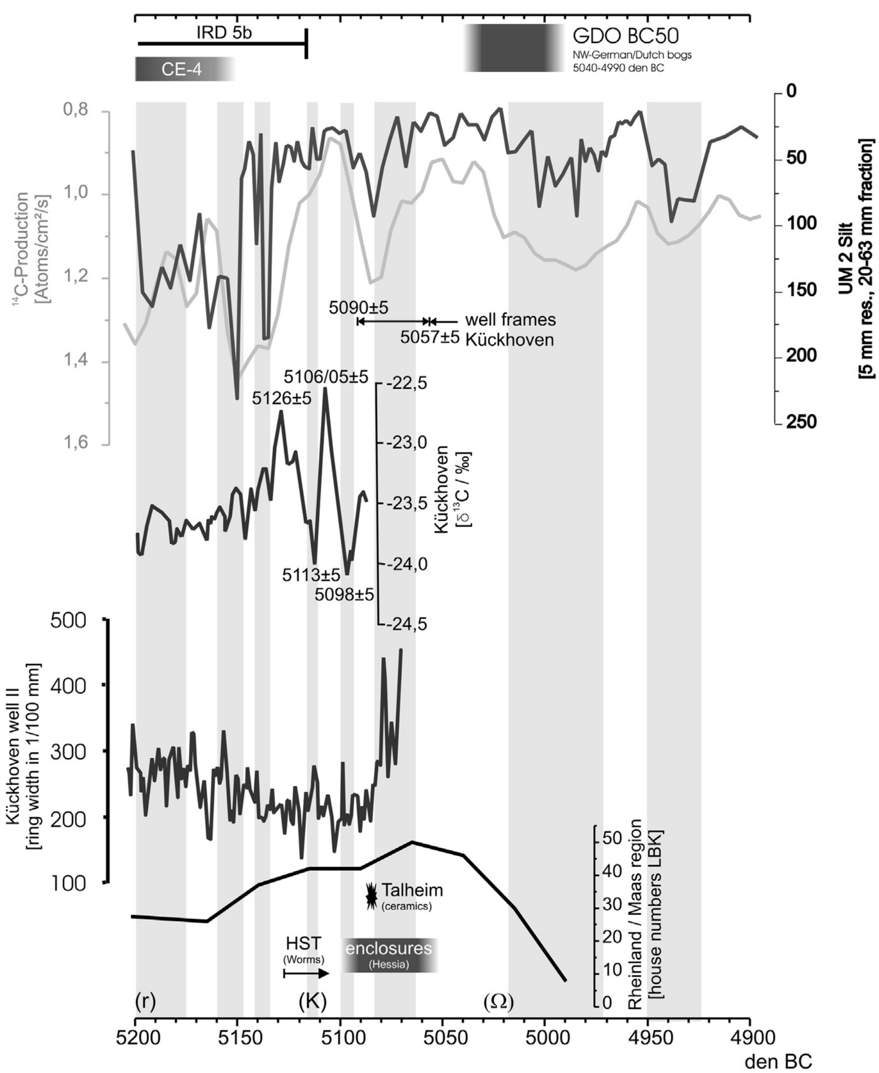

Fig. 6. Palaeoclimatic proxy-data for the end of IRD 5b and archaeologically dated events towards the termination of LBK. Phases of increased rainfall are shaded (IRD 5b: Bond et al., 2001; Alpine cold event 4 (CE-4): Haas et al., 1998: germination-dying-off-event (GDO) BC50: Leuschner et al., 2002; ^{14}C-production rate: Kromer and Friedrich, 2007; δ^{13}C Kückhoven: Helle and Schleser, 1998; Helle and Heinrich, 2012; tree ring-width Kückhoven: Schmidt et al., 1998; house numbers Rheinland/Maas region, ceramic dating Talheim: Strien; onset Middle Neolithic [Hinkelstein – HST]: Jeunesse and Strien, 2009; enclosures Hessia: Kerig, 2008).

chronology is mostly based on dendrochronological dates from Kückhoven and within slight dating uncertainties also from Mohelnice (Strien and Gronenborn, 2005). The stratigraphic soundness of both the dendrochronological as well as the typological dates is ascertained by the dimension of the logs and the rapid refilling of the bottom part of the feature (Hinzen and Weiner, 2009).

Considerable and numerous uncertainties in radiocarbon dating during the period of the LBK lead us to largely abstain from using ^{14}C-dates for a fine-grained chronology. One of the major problems are caused by the ^{14}C-plateau at the time in question (Petrasch, 1999; Bánffy and Oross, 2010), particularly the period between 5250 and 5050 cal BC cannot be resolved. Also, the early expansion of LBK appears to have been so fast, that it is not possible to fine-date it by ^{14}C (Frirdich, 2005, 86). Another rather simple explanation for some dating problems is bioturbation which resulted in the infilling of younger material into older features not only for long-term occupation sites but also for abandoned settlement locations which had continued to be used as farming plots (Strien and Gronenborn, 2005). These and other yet unsolved problems may be the cause for contradictions between ^{14}C-dates and typology-based regional chronologies (Petrasch, 1999). For instance do the earliest ^{14}C-dates for eLBK from the site of Schwanfeld date between 5484 and 5350 cal BC (Lüning, 2005), the latest from the eLBK from the site Rottenburg fall into the 50th and 49th centuries (Bofinger, 2005; fig. 71). These sites are only about 200 km apart (Fig. 1) and their ceramic assemblage is very similar. Also, both regions undergo a consecutive development towards later LBK and further on towards the early Middle Neolithic. Given these typologically synchronic developments in neighbouring regions a time difference of 300 ^{14}C-years appears highly improbable. Uncertainties also become evident when ^{14}C-based chronologies are interpreted: While for instance Stäuble and Cladders (2003, 496) prefer eLBK to have started around 5550/5500 cal BC, Stadler and Kotova (2010, 320) opt for a beginning around 5300 cal BC, however Bánffy and Oross (2010) again consider a beginning around 5600/5500 cal BC.

These numerous problems with the currently available ^{14}C-data set lead us to the conclusion that a fine-grained chronology at the current state of research has to be based first and foremost on typology and reliable and robust anchor dates like from the wooden well of Kückhoven. Future ^{14}C-dating projects for LBK should gear for securely stratified material preferably from short-term small and isolated sites whose plots would have been completely abandoned after occupation.

Still, also the method applied by us has its pitfalls as archaeological reconsiderations of the association of pottery within the Kückhoven well has led to slight changes in comparison to earlier published versions (Strien and Gronenborn, 2005; Bogaard et al., 2011; Gronenborn, 2012). Nevertheless, this chronological system is fairly reliable and operable in the western region of the LBK where the decoration system of the ceramic assemblages is chronologically sensitive. In the more easterly provinces ceramic styles are more stable and fine-grained typochronological methods might fail.

5. Cycles and climate fluctuations

Based on the above discussed chronology LBK in western Central Europe may be interpreted as representing an entire cycle (Fig. 4). The LBK cycle begins with two early Neolithic groups at the northeastern fringes of the Balkan – the Balaton- and Danube-LBK – which left their regions of origin and reached the Rhine river within one generation (Fig. 1) (Strien, 2009). The earliest phase of LBK (eLBK) in the west is constituted by the migrants from the Carpathian Basin together with the regional Terminal Mesolithic hunter–gatherers, hunter–gatherer–horticulturalists or horticulturalist–pastoralists of the La Hoguette group (Strien, 1996; Jeunesse, 2001; Gronenborn, 2007a,b). This eLBK period comes to an end around 5380 denBC with a number of settlements being abandoned or dislocated. As a formative period it may be given the attribute of the LBK α-phase.

The consecutive r-phase would be the earlier LBK, or Flomborn-phase (LBK II after Meier-Arendt, 1972) during which new settlements were founded and new regions like the Rhineland and Alsace settled (Fig. 1). Site sizes increase with up to 50 contemporary houses like at Vaihingen/Enz (see below). Farming is extensive and accessibility of farmland was apparently organized by social entities like lineages or clans (Bogaard et al., 2011). This period may be given the attribute of an r-phase.

The developed or younger LBK (yLBK) sets in around 5180 denBC. Apparently farming practices intensified as the compound areas are now much larger with contemporary structures being much more distant from each other. This may be due to the fact that fields and gardens were now located in the immediate vicinity of the long-houses. At the same time the number of contemporary houses within settlements decreases. Possibly, individual compounds now constitute the basic unit of the farming method (Bogaard et al., 2011). This would be the period of the K-phase.

During yLBK features per HG increase (Fig. 4). This increase may translate into population growth as the number of pits correlates to the number of houses and so indirectly to an increase in the population rate. Two expansion events occur during this final phase, one around 5125 denBC and one around 5050 denBC (Fig. 4). This is the period of massive internal conflicts as indicated by the sites of Talheim and Schletz (Wild et al., 2004) and others. In Hessia enclosures – interpreted as village fortifications – are being constructed in a period between 5100 and 5050 denBC (Kerig, 2008) (Fig. 6). After 5080 denBC LBK vanishes in Württemberg, somewhat later in the Rhineland and after 5000 denBC LBK also disappears in the Paris Basin. This would be the Ω-phase.

The overarching cycle may be subdivided into shorter ones (Figs. 4 and 5). For the earliest LBK the first two to three HG may be understood as its α-phase. Pioneer settlements were established, regional networks operated and the economy had stabilized. During the fourth to sixth HG population increased (Strien, 2000); this increase constitutes the r-phase. The last third of eLBK does not show any further population increase and may thus be interpreted as its K-phase.

The internal dynamics of LBK II and yLBK societies are particularly apparent from data form the site of Vaihingen/Enz in SW Germany (Krause, 1998; Bogaard et al., 2011; Supplementary online data). With its 18 consecutive HG Vaihingen is well suited for long-term studies like for instance the rate of change in ceramic decoration. This rate of change is expressed by an index calculated by adding up positive or negative differences in the sum of all decoration types between two consecutive phases. The resulting value lies between 0 – no change – and 1 – complete change of the spectrum. If the rate of change in ceramic decoration per HG is plotted against the time-line phases with increased developmental speed become apparent (Fig. 5).

The decoration mode changes much more rapidly during the transitional periods of eLBK–LBK II and LBK II–yLBK. These changes seem to be connected to transformations in information coding on ceramics. During eLBK socially relevant information such as group affiliation were carried by the main motifs, during LBK II these contents seem to have been carried by the secondary motifs (Bogaard et al., 2011). Social changes may be behind this shift in information coding, possibly the social structure of the eLBK had undergone a process of reorganisation (Frirdich, 2005). Both of these periods of rapid typological and possibly social change may

be understood as α-phases. The preceding phases of decline both of the eLBK and LBK II are characterized by the expansions into the Rhineland and to Alsace (Heinen, 2010; Hoppe, 2012; Lefranc, 2007). LBK II brings a number of novelties like extensive settlements and the onset of burial grounds like Flomborn itself (Richter, 1968/69).

At Vaihingen, house numbers decrease at the end of LBK II. The following reorganisation with an enlargement of the compounds (from an average of 517 m^2 to about 2000 m^2) went along with a relocation of some houses and with distant farming plots being abandoned (Bogaard et al., 2011, 408). This change is completed at the beginning of the yLBK when a new r-phase sets in with a slight population increase starting towards 5150 denBC. Around 5100 denBC the situation stabilizes (K-phase) and after 5090 denBC the final deterioration sets in with a population decline (Ω-phase). The decline at Vaihingen is part of the general LBK-decline towards the end of the sixth millennium. Now the yLBK cycles joins the overall LBK cycle.

When the dynamics of LBK outlined above are compared to palaeoclimatic proxy-data available for sixth millennium Central Europe, some concurrences become evident. This had been observed before (Schmidt et al., 2004; Strien and Gronenborn, 2005; Dubouloz, 2008; Gronenborn, 2012) but can now be chronologically fixed more precisely and is also understood in greater detail (Figs. 4 and 6). However, with the now applied chronological model and its resolution of decades only few immediate correlations between climate fluctuations and socio-economic processes may be observed (As we not yet fully included eLBK in our analyses we here abstain from any statements about the emergence and spread of eLBK and possible correlations with climate fluctuations).

Developed eLBK is contemporaneous to the fluctuation of 5410 denBC (Fig. 4). Contrary to earlier attempts to align LBK chronology with palaeoclimatological age models (Strien and Gronenborn, 2005; Gronenborn, 2012) an immediate effect as a 'triggering force' for the expansion to the Rhineland and Alsace around 5390–5350 denBC cannot be postulated any more. The fluctuation of 5410 denBC precedes the expansion by about one generation. The fluctuation around 5240 cal BC (Fig. 4) equally does not appear to have had major negative wide-spread socio-economic effects and is not particularly visible in the Kückhoven record (Helle and Heinrich, 2012, 60). Contrary to the earlier hypotheses both fluctuations may however have had slight positive effect on the population rate as discussed further below. Typologically LBK II ends around 5180 denBC which is not associated to any currently recognized major climate events.

Only the subsequent period of climate fluctuations might have had a more consequential effect on LBK. Particularly the period between 5140/30 denBC and 5090/80 denBC was characterized by strong fluctuations between rather dry and unusually wet conditions with the years 5106/05 denBC likely being very dry with possibly rather high temperatures (Helle and Heinrich, 2012, 60). This is the termination period of IRD 5b with a considerable change in the ^{14}C-production rate (Figs. 4 and 6). These volatile fluctuations are contemporaneous to the emergence of HST, the construction of enclosures around settlements and indications of violence as in Talheim and Schletz (Wild et al., 2004). At the same time LBK in the west reached its highest population densities, contemporary to increased rainfall after 5098 denBC. According to the ^{14}C-production curve and the UM2 silt curve another period of decreased rainfall follows after 5070/60 denBC, lasting to about 5030/20 denBC. This is supported by data from the NW-German/Dutch bog oaks where a germination-dying-off-event is recorded for the period between 5040 and 4990 denBC, indicating increased precipitation (Leuschner et al., 2002) but also again from the ^{14}C-production curve as well as the UM2 silt curve (Fig. 6). Thus the terminal LBK would have existed during another period with decreased rainfall. Generally dryer conditions are also indicated by a change in settlement patterns as late and latest LBK sites shift to higher elevations in Hessia (Gronenborn, 2012) but also in Alsace (Lefranc, 2007), locations which today at least in Hessia are too wet for farming. Generally, LBK in western Central Europe vanishes between 5050 denBC and 5000/4950 denBC, being replaced by HST in the Upper Rhine Valley, the Neckar Valley and Lower Alsace (Jeunesse and Strien, 2009). LBK in the Rhine-Maas area disappears shortly after 5000 denBC (Fig. 6) with the region only being repopulated again by the Middle Neolithic Großgartach group (Spatz, 1996; Kalis and Meurers-Balke, 1997).

The above scenario does follow the theoretical prerequisites formulated by Coombes and Barber (2005) for potential cases of climate-induced culture change: in the course of its decline LBK marginal zones like the Rhineland become abandoned, changes in modes of agricultural production would be reflected in changes in settlement pattern both for terminal LBK and HST, and the collapse of social organisation is indicated by the transition to HST. This transition, with its changes in the iconography of pottery decoration and in burial practices has been interpreted by Spatz (2003) as being ideologically motivated. Such changes in ideology may well be the result of social changes due to responses to external threats like climate fluctuations. It may also be reminded that the irregular interments at Herxheim with possible indications of cannibalism date to this period (Boulestin et al., 2009).

It is important to stress that LBK did not collapse during a period of intensified warfare and conflict but rather declined after such a period. In many cases enclosures were backfilled intentionally, indicating that their primary function had gone out of use (e.g. Wotzka et al., 2001). Thus, as exemplified by a number of other case studies world-wide in McAnany and Yoffee (2010), LBK societies did not collapse and vanish at once but rather declined and transformed into the Middle Neolithic societies. Anthropological studies equally show no immediate break between LBK and HST populations at least for the Upper Rhine Valley (Meyer and Alt, 2005). Whether and exactly how the considerable climate fluctuations between 5150 and 5000 denBC affected LBK needs to be investigated in more detail by analysing sites from particularly that period. As a matter of fact, the abandonment of the Rhineland settlement cluster has previously been interpreted without any reference to climate fluctuations (Frirdich, 1994; Claßen, 2011).

While any simple correlation of climate fluctuations and immediate societal response is put into perspective by the data presented, nevertheless the LBK evidence does suggest that population growth may have been related to precipitation rates. Growth rates decreased during periods with presumed or observed decreased rainfall (Figs. 4 and 6). This interrelation becomes particularly apparent at the end of the LBK for which two rather dry years have been postulated (Fig. 6). In contrast, population rates increased during periods of presumed or observed increased rainfall (Figs. 4 and 6). Commonly, periods with increasing rainfall would be considered as adverse in a temperate European environment (e.g. Dubouloz, 2008; Kreuz, 2010, 53). However the reverse interconnection suggested here may be explained by an analysis of Bleicher (2011) who postulated that particularly during the mid-Holocene periods of decreased or irregularly spaced rainfall might have posed considerable threats for harvests.

Taken these connections into consideration the climate fluctuations of 5410 denBC, 5420 denBC and 5150 denBC, which before were interpreted as having had negative effects (see above; Fig. 4) might have actually constituted favourable periods during which population grew. Why this was the case, will have to be investigated by future fine-grained studies on time-series of LBK crop yields and their relation to population figures.

6. Conclusions

Cycle-based resilience theory is increasingly seen as an appropriate theoretical tool in understanding past processes through a socio-environmental approach for a variety of societal types (e.g. Dearing, 2008; McAnany and Yoffee, 2010). It also seems to be helpful in approaching the dynamics of the simple farming societies of the Early Neolithic in temperate Europe.

Generally LBK dynamics appear to have had an inherent component of expansion and population growth (Petrasch, 2001, 2012; Frirdich, 2005) which would follow the theoretical presetting that many systems tend towards greater complexity (Coombes and Barber, 2005). LBK sub-phases may be interpreted as representing cycles which were structured by expansion events and phases of internal social intensification and reorganization. These internal processes were punctuated by climate anomalies of which particularly those of the terminal sixth millennium were directly associated to negative social and economic consequences.

Resilience theory with its emphasis on the capacity of societies to react to external or internal stress factors helps to understand why and how LBK managed to solve challenges for many centuries without collapse or major reorganisation. Societal resilience grew during climatically favourable periods of prosperity and lowered in subsequent periods of adverse climate (Fraser, 2007). This complex interplay continued until the last two centuries of the sixth millennium when western LBK societies – after a considerable and never before experienced population increase – suddenly faced a period of climate instability which persisted for many decades. With population and complexity threshold levels almost reached, resilience weakened. Western LBK societies had increasing difficulties in adapting to the rapidly changing climatic conditions and to the general trend towards less rainfall. These challenges were, however, mastered by the Middle Neolithic Hinkelstein societies who seem to have operated successfully in the same general environment. For reasons yet entirely unclear, their socio-economic system had proven more resilient. Also, terminal LBK societies in eastern Central Europe appear not to have collapsed to the same degree as they had in the west. Possibly their economies and social systems had been less vulnerable to the challenges of the terminal sixth millennium than those of the more western settlement clusters.

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Appendix A. Supplementary material

Supplementary material associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jas.2013.03.015.

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